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Global Biogeochemistry Models and Global Carbon Cycle Research at Lawrence Livermore National Laboratory

C. Covey, K. Caldeira, T. Guilderson, P. Cameron-Smith, B. Govindasamy, C. Swanston, M. Wickett, A. Mirin, D. Bader

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Informal report in response to request from the DOE Office of Science, Climate Change Research Division

Curt Covey, Ken Caldeira, Tom Guilderson, Philip Cameron-Smith, Bala Govindasamy, Christopher Swanston, Mike Wickett, Art Mirin, and Dave Bader

POC: Dave Bader
Mail Code L-103
Lawrence Livermore National Laboratory
7000 East Avenue
Livermore, CA 94550

Phone: 1-925-422-4843
Email: bader2@llnl.gov

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The climate modeling community has long envisioned an evolution from physical climate models to "earth system" models that include the effects of biology and chemistry, particularly those processes related to the global carbon cycle. The widely reproduced Box 3, Figure 1 from the 2001 IPCC Scientific Assessment schematically describes that evolution. The community generally accepts the premise that understanding and predicting global and regional climate change requires the inclusion of carbon cycle processes in models to fully simulate the feedbacks between the climate system and the carbon cycle. Moreover, models will ultimately be employed to predict atmospheric concentrations of CO_2 and other greenhouse gases as a function of anthropogenic and natural processes, such as industrial emissions, terrestrial carbon fixation, sequestration, land use patterns, etc.

Nevertheless, the development of coupled climate-carbon models with demonstrable quantitative skill will require a significant amount of effort and time to understand and validate their behavior at both the process level and as integrated systems. It is important to consider objectively whether the currently proposed strategies to develop and validate earth system models are optimal, or even sufficient, and whether alternative strategies should be pursued. Carbon-climate models are going to be complex, with the carbon cycle strongly interacting with many other components. Off-line process validation will be insufficient. As was found in coupled atmosphere-ocean GCMs, feedbacks between model components can amplify small errors and uncertainties in one process to produce large biases in the simulated climate. The persistent tropical western Pacific Ocean 'double ITCZ' and upper troposphere 'cold pole' problems are examples. Finding and fixing similar types of problems in coupled carbon-climate models especially will be difficult, given the lack of observations required for diagnosis and validation of biogeochemical processes.

For example, we have very little understanding of long-term acclimation of terrestrial biological systems to changes in atmospheric CO2 and climate, after ecosystems, nutrients, and soil biogeochemistry adjust to new conditions. Land management may play an important role in shaping ecosystems. A much more detailed and comprehensive understanding of the roles of nutrient cycles, CO2-fertilization, water, temperature, etc is needed to improve our predictive capabilities for multi-decadal evolution of carbon stocks on land ecosystems. Modeling the ocean component is similarly problematic. There has been no sound quantitative study of the relative importance of various process uncertainties in making carbon-cycle predictions on the multi-decadal time scale. The relationship between model ecosystem complexity and predictive skill for the problem of predicting multi-decadal carbon exchange has yet to be demonstrated. Perhaps global ocean carbon modeling needs to be put on a firmer physical basis, so that its equations describe a physically well-defined system, or perhaps very simple parameterizations have all the skill we will ever need. It seems that it would be good to address these issues, and then try to build a model consistent with the answers to those questions.

We propose, as a first step, that the CCSM community build on the lessons learned from the C4MIP experiment to try to isolate the carbon cycle feedbacks simulated in the coupled carbon-climate models through a second intercomparison of the different carbon cycle models all coupled to a standard version of the CCSM climate model. Hardware and software engineering will be required to make it feasible to run such an intercomparison, but the standardization done through the CCSM coupler development and the Earth System Modeling Framework may make such an effort tractable. We would like to explore this possibility with our sister laboratories, NCAR and other carbon cycle researchers.

Below are our responses to the specific questions posed in Dr. Elwood's April 7, 2005 memorandum. Additionally, LLNL researchers, both alone and in collaboration with external researchers, have a long publication history in modeling, diagnosing, and understanding the climate and the carbon cycle (and related processes). Copies of the relevant papers are included in the package accompanying this whitepaper.

(1) Scientific and technical capabilities in carbon cycle modeling at LLNL

LLNL's modeling capabilities are located mainly in the Carbon and Climate Science Group (CCSG) within the Energy and Environment Directorate. (LLNL also has high-precision carbon isotope measurement capability, described below.) The CCSG recently developed the INtegrated Carbon and Climate Assessment (INCCA) model—which fully couples the ocean carbon cycle, the terrestrial carbon cycle and the physical climate system on a global scale—and has published three INCCA papers in the peer-reviewed technical literature during the last two years.[1-3] INCCA is the first (and the most extensively used) three-dimensional ocean / atmosphere / carbon cycle model developed in the USA. It is one of several models contributing output to the international Coupled Climate-Carbon Cycle Model Intercomparison Project (C4MIP).[4]

In addition to INCCA, LLNL has a variety of models simulating ocean carbon sequestration. Most use variations of the Ocean Carbon-Cycle Model Intercomparison Project (OCMIP) protocols for simplicity and transparency (as does INCCA). Results from these models have appeared in several high-impact peer-reviewed technical journals.[5-8]

Atmospheric chemistry and aerosols have long been modeled at LLNL. Most recently, the CCSG developed a state of the art "off-line" 3D global model (IMPACT) that simultaneously encompasses the troposphere and stratosphere at high resolution. As we discuss below, IMPACT's modeling capability has allowed implementation (and publication in the peer-reviewed literature) of a number of studies directly related to carbon cycle modeling.

This group is also intimately involved with the SciDAC Consortium in incorporating IMPACT's chemistry and aerosol simulation on-line into the CCSM, along with terrestrial and oceanic biogeochemistry. This coupled carbon-climate model is distinct from the INCCA model, with totally different biogeochemistry modules, although they are both implemented in CCSM3.

(2) Role LLNL is playing in CCSM Working Groups that are dealing with carbon cycle and other biogeochemical modeling

CCSG scientists are members of the Atmospheric, Biogeochemical, Climate Change and Software Engineering Working Groups, together with the Atmospheric Chemistry Working Group (formed recently with the participation of CCSG). LLNL scientist Ben Santer co-chairs the Climate Change Working Group, which will likely become more involved in biogeochemical issues as the carbon cycle is included in simulations of climate change.

(3) Status and capabilities of global ocean and terrestrial carbon cycle models at LLNL

The CCSG has implemented modified OCMIP algorithms for carbon cycle simulation in the GFDL Modular Ocean Model and in the ocean component of the DOE-sponsored Parallel Climate Model (PCM). The CCSG has also used several different ocean biogeochemistry models for studies of both the natural carbon cycle and ocean carbon sequestration.

Through LDRD investments, CCSG has coupled the IBIS terrestrial model from John Foley of the University of Wisconsin with the PCM to form INCCA. The CCSG is moving forward with development of an INCCA replacement that uses CCSM in collaboration with LANL and ORNL. Part of that collaboration includes testing the PISCES ocean / carbon cycle model (from Pierre Friedlingstein, Institute Pierre Simon Laplace, France) and developing a more detailed ocean biogeochemistry model.

The IMPACT atmospheric chemistry and aerosol model is fully validated[11]. Atmospheric chemistry and aerosols are currently being combined with the CCSM under the SciDAC consortium. The individual components have been validated, and the combined model is scheduled to be connected together by the end of June 2005.

(4) Testing of model performance

The CCSG participated in both C4MIP and OCMIP, and in a series of papers explored the use of chlorofluorocarbons, radiocarbon, salinity and temperature to evaluate alternate assumptions in ocean / carbon cycle models. LLNL is cooperating with NASA to use satellite data to evaluate OCMIP results.

In the coupled climate and carbon cycle (INCCA) framework, simulation results indicate that (a) the carbon cycle can provide a significant positive feedback on global warming during the next 100 years, provided land and ocean carbon sinks saturate in the near future,[1] and (b) very significant global warming—essentially sending Earth back to the Cretaceous climate last seen in the age of the dinosaurs—is inevitable over longer (~300 year) time scales if the world burns most of its coal reserves.[3] Figures 1 and 2 (at the end of this paper) show examples of these results.

The IMPACT model has been tested by investigation of the following processes, which can influence the carbon cycle by affecting biological productivity: (1) anthropogenic nitrogen emissions,[9] ozone amounts[10-11] and wind-blown dust[12] (which can fertilize the iron-limited oceans).

(5) Models that have been coupled to a GCM

The ocean / carbon cycle models discussed above all contain biogeochemical sub-models coupled with ocean GCMs. The INCCA model discussed above contains biogeochemical sub-models (both marine and terrestrial) coupled with both an ocean GCM and an atmosphere GCM. In addition, the CCSG has coupled IBIS with the CCM3.6 atmosphere GCM plus a simple (“slab”) ocean sink model, with the CAM atmosphere GCM and in collaboration with LANL and ORNL, with the CCSM coupled ocean-atmosphere GCM.

The IMPACT aerosol and chemistry model has been coupled to the CAM atmosphere GCM, in preparation for coupling to the full CCSM as described above.

(6) Additional work required to improve / test models so they can be coupled to a full physical climate system (atmosphere-ocean-ice-land) model such as CCSM3

LLNL has achieved this with the INCCA model as noted above, using the PCM to simulate the physical climate system. Transition to the CCSM3 should be straightforward: as noted above, the IBIS terrestrial carbon cycle model is already coupled to the CCSM, leaving the ocean carbon cycle as the remaining process that needs to be incorporated. Coupling of IMPACT with the CCSM is expected very soon, as described above.

(7) Software engineering to improve model efficiency

The CCSG has converted the IBIS code to run in parallel in a scalable and load-balanced manner, and intends to port the code to the Cray X1. The CCSG has also contributed to software improvements in the CCSM through the DOE Scientific Discovery through Advanced Computing (SciDAC) consortium. Examples include MPI communications and vectorization of the finite-volume dynamics "core" of the code, and porting of the CCSM to an IA64 Linux cluster.

(8) Other biogeochemical modeling activities at LLNL

LLNL is the home of the Center for Accelerator Mass Spectrometry (CAMS), a multi-isotope facility utilized by the domestic and international community. Of relevance to carbon-climate studies are the radiocarbon (^{14}C) capabilities of CAMS. Research projects involving CAMS span the breadth of the carbon cycle and its reservoirs (ocean, atmosphere, terrestrial) on time scales ranging from "event" to millennia.[13-19] CAMS is the analytical base for the university and multi-laboratory (ORNL, LBL, LLNL) Enriched Background Isotope Study (EBIS). CAMS is helping provide new and accurate carbon flux data for input into the EBIS-based modeling efforts led by ONRL, including participation in model development. Most recently, CAMS has demonstrated 1-2‰ accuracy in measurements on archived CO_2 collected as part of the UC San Diego / Scripps Institution of Oceanography flask network.[20] CAMS is currently engaged in a pilot program to demonstrate the utility of these measurements.

CAMS scientists are also working with the US Geological Survey and the University of Colorado to improve representation of the carbon cycle in a biogeochemical soil model, with the eventual goal of incorporating it into larger-scale biogeochemistry models.

(9) Factors limiting progress in carbon cycle and carbon-climate modeling

- Observational data base

  Observations seem wanting in terms of quantities suitable for direct comparison with carbon-cycle model output, compared with quantities suitable for direct comparison with physical climate system model output. Intercomparison of methods (inversion models) for producing carbon-cycle data may improve the situation.[21] Tracers that are tightly coupled to the carbon cycle can provide information on carbon sources and sinks, but this requires both improvements to the observational data base* and incorporation of appropriate diagnostic quantities into the models (see below). The utility of multi-tracer ([CO_2], $\delta^{13}C$, O_2/N_2, $\Delta^{14}CO_2$) diagnosis of carbon fluxes is unparalleled, especially for testing the models' terrestrial biosphere parameterizations.

There is also very little observational basis for predicting long-term ecosystem adjustment to changes in atmospheric CO2, climate and land use.

- Including all relevant processes in carbon cycle / climate models (and deciding which processes are relevant via sensitivity testing and model intercomparison):
    - Anthropogenic aerosols
    - Anthropogenic land-use change
    - Dissolved organic (in addition to inorganic) carbon:
        - In land ecosystems
        - In the oceans
    - Biochemically important atoms in addition to C:
        - N
        - S
        - Fe
    - Spatial distributions of CO2 and isotopes (as diagnostics)—in particular atmospheric $^{14}CO_2$ *

* See remarks on the LLNL Center for Accelerator Mass Spectrometry (CAMS) above.

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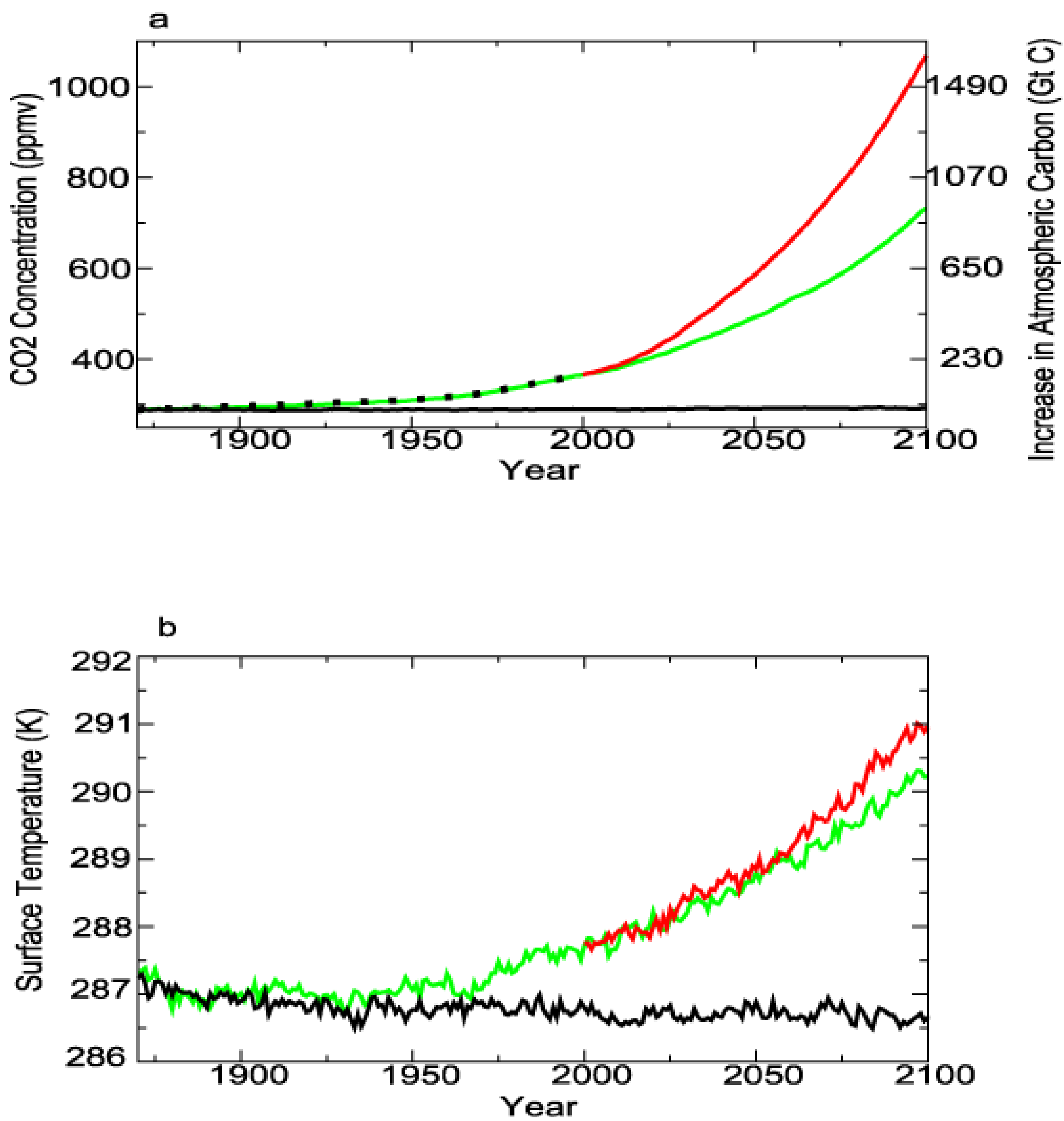

Figure 1 (= Figure 1 in Reference (1)): Atmospheric CO2 levels (*top*) and globally averaged surface temperature (*bottom*) simulated by the three-dimensional coupled ocean / atmosphere / carbon cycle INCCA model. Black dots are observed amounts. The black lines show results from the model's "control run," i.e. assuming no human effect on the carbon cycle. The colored lines show results with anthropogenic carbon dioxide emission specified at historical levels for 1870-2000 and prescribed for the 21st century according to the A2 (continuously increasing population) scenario of the Intergovernmental Panel on Climate Change (IPCC). Green lines show results assuming no saturation of carbon sinks; red lines show results assuming saturation occurs immediately at the present moment. These two assumptions bound the range of plausible behavior of the real Earth. The differences between the red and green curves demonstrate substantial uncertainty in future positive feedback of the carbon cycle on global warming.

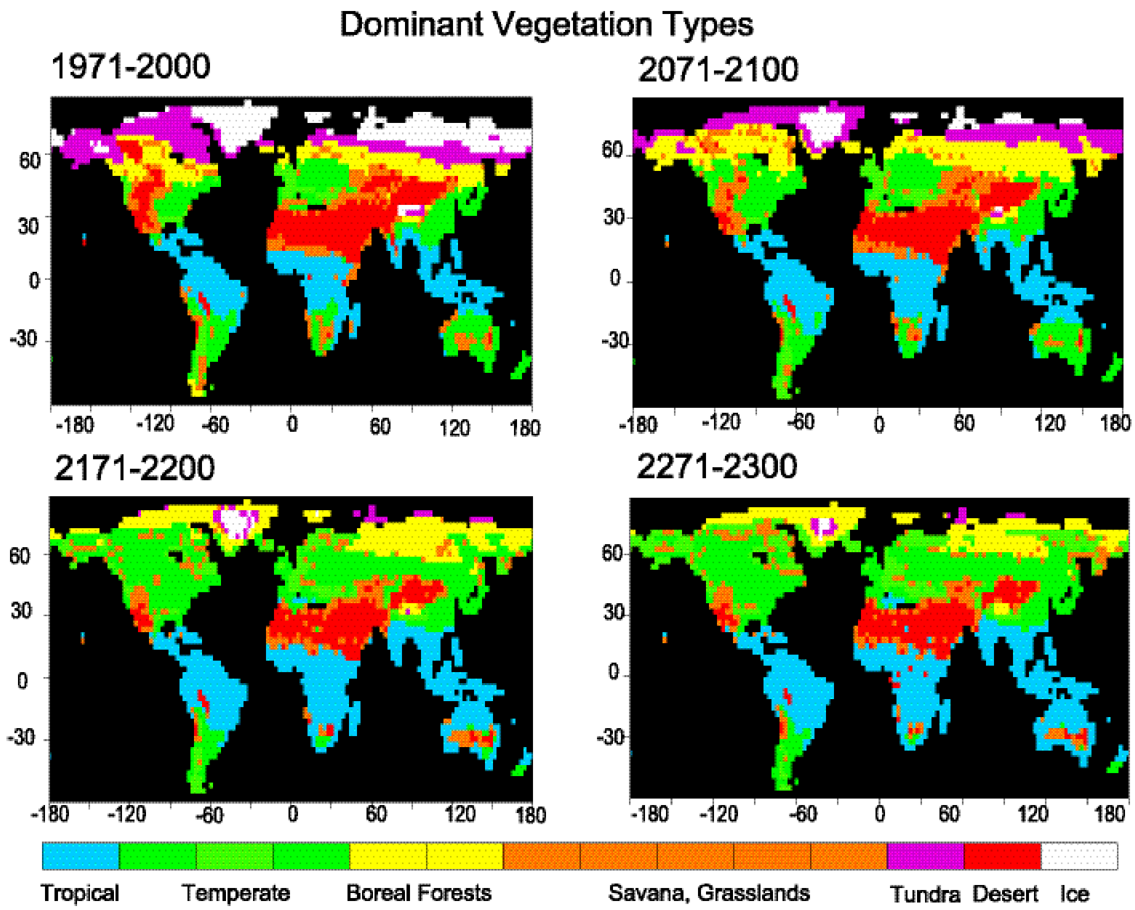

Figure 2 (= Figure 8 in Reference (3)): Vegetation simulated by the INCCA model for the present day (*upper left*) and for future time periods under the IPCC A2 scenario of anthropogenic CO2 emission. The area covered by tropical and temperate forests increases dramatically by the year 2300 (*lower right*), when the model simulates a global surface temperature distribution averaging ~8 K warmer than the present day. Note, however, that the model does not include the direct effect of land-use change on vegetation (e.g. deforestation). The simulated vegetation is therefore what would occur "naturally" given the simulated climate change.